

A Comparison of GPS Performance in a Scintillation Environment at Ascension Island

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BIOGRAPHY

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ABSTRACT

Post-sunset disturbances in the equatorial ionosphere routinely cause rapid phase and amplitude fluctuations (i.e., scintillation) of radio waves propagating through the disturbed regions. The intensity of scintillations is positively correlated with the solar cycle and the associated signal fades will often exceed 20 dB at L-band frequencies during solar maximum. The effect of such an environment on the performance of GPS navigation systems is poorly understood. In March 2000 AFRL conducted a campaign at Ascension Island to test the performance of several GPS receivers under potentially severe scintillation conditions. Ascension Island is located at approximately 16° S magnetic latitude, a region of intense ionospheric disturbances. The systems tested included a Plessey GPS Builder, a Novatel-based prototype GPS Silicon Valley (GSV) Ionospheric Scintillation Monitor (ISM) modified specifically for scintillation applications, a custom High Gain Advanced GPS Receiver (HAGR) developed for AFRL by NAVSYS Corporation and an Ashtech Z-12. Overall, the Ashtech proved to be very robust at tracking the carrier signal amplitude and phase, but it experienced

scintillation-induced navigation outages on four of the eight nights of observations. The responses of the different receivers during severe scintillation varied significantly, suggesting that models to simulate ionospheric effects on GPS performance must be receiver-specific.

INTRODUCTION

The ionosphere is a partially ionized (plasma) region of the earth's upper atmosphere that extends from approximately 60 km to 1000 km altitude. Ionization modifies the refractive index of the neutral atmosphere and, when it becomes structured or turbulent, can cause strong scintillation of radio waves passing through the disturbed region. Scintillation refers to rapid phase and amplitude fluctuations of the radio signals observed on or near the earth's surface. If sufficiently intense, these fluctuations can dramatically impact the performance of space-based communication and navigation systems.

Both high and low latitudes are subject to this phenomena, but low latitude effects are significantly larger because the electron density, and thus the absolute refractive index variation, is much greater near the equator. The affected region spans approximately $\pm 15^\circ$ magnetic latitude (centered on the earth's magnetic equator) and covers about one third of the earth's surface. The plasma medium becomes turbulent after sunset in the presence of steep vertical gradients in electron density. Upwelling of low density plasma from the bottomside of the ionosphere into the higher density regions above and subsequent gradient-driven instabilities lead to structuring (turbulence) on the scale sizes needed to produce the observed scintillations (1 km ~ 100 m).

In an effort to better understand scintillation phenomena and quantify its impacts on GPS navigation, the Air Force Research Laboratory (AFRL) is interested in monitoring scintillation activity globally [Groves, et al., 1997].

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Under an effort initiated in the early 1990s, AFRL supported the development of a specialized GPS scintillation monitor based on a modified Novatel single frequency receiver. These receivers were the prototypes for the improved GPS Silicon Valley (GSV) 4000 and 4001 series receivers. Called Ionospheric Scintillation Monitors (ISMs), the modified receivers provide processed scintillation parameters for up to 11 GPS links simultaneously. These parameters include the normalized standard deviation of the signal intensity (S_4) and the standard deviation of the phase (σ_ϕ); in addition, it is possible to record raw (50 Hz) amplitude and phase data on up to 3 links.

The most severe natural scintillation in the world occurs in the nighttime equatorial ionosphere. To monitor this region the ISM receivers were deployed at a number of low latitude sites and functioned well through the mid-nineties, a period of low solar activity. As solar output, and correspondingly, L-band scintillation, increased beginning in 1998, however, it became apparent that the ISMs were unable to reliably report scintillation levels above an S_4 of 0.8 or so. Such levels are routinely experienced at low latitudes during solar maximum (~2000-01), the period of most severe scintillation activity and the most critical time to accurately assess effects on GPS. In March-April 2000, AFRL conducted a measurement campaign at Ascension Island (8°S, 14°W) to investigate equatorial scintillation dynamics and evaluate the performance of several GPS receivers during strong scintillation. The preliminary results of the campaign and their implications for modeling scintillation impacts on GPS navigation are described below.

EXPERIMENTAL

Data was collected from four GPS receivers at Ascension Island from 27 March-03 April, 2000. Moderate to strong scintillation occurred on six of the eight nights, with four nights exhibiting strong ($S_4 \geq 0.8$) scintillation. The receivers tested were the Ashtech Z-12, the Plessey GPSBuilder, the High Gain Advanced GPS Receiver (HAGR) and the ISM. AFRL was particularly interested in the dual-frequency Ashtech because of its capability to provide total electron content (TEC) data as well as phase and amplitude scintillation. Carrier-to-Noise ratio (C/N₀; L1 only) and signal phase (L1 & L2) were recorded at a 20 Hz rate on the Ashtech; position and satellite tracking data were sampled once per second.

The Plessey was operated to obtain C/N₀ at a 10 Hz rate and employed a frequency-locked-loop for signal tracking which precluded useful phase scintillation measurements. Because it can record raw data on at most three satellites at any given time, no raw data was recorded with the Novatel. Rather, processed scintillation parameters from all available satellites were recorded every 60 seconds for

comparison with the other receivers. None of the other receivers currently have real-time parameter processing capability.

The HAGR is a prototype phased-array software-based receiver that was developed by NAVSYS Corporation under the sponsorship of AFRL [Brown et al., 2000]. Utilizing digital beamforming technology, the HAGR can obtain 8-12 dB gain on each of up to eight GPS satellites and should, therefore, provide superior signal tracking through strong scintillation. The Ascension test was the first field “shake-out” of the system, however, and the HAGR frequently experienced signal drop-outs and large navigation errors, principally due to bugs in the code which were not evident in tests conducted at mid-latitudes under non-scintillating conditions. Because we believe its performance at Ascension in the 2000 campaign was not representative of its true capabilities, the HAGR data are not included in the analysis presented here. Changes to the software have since been implemented and additional measurements are planned in the future.

RESULTS

Scintillation Monitoring

Figure 1 shows an example of data recorded on the Plessey, Ashtech and ISM on the night of 27 March 2000. The results are representative of the strong scintillation nights during the campaign. The two upper panels show

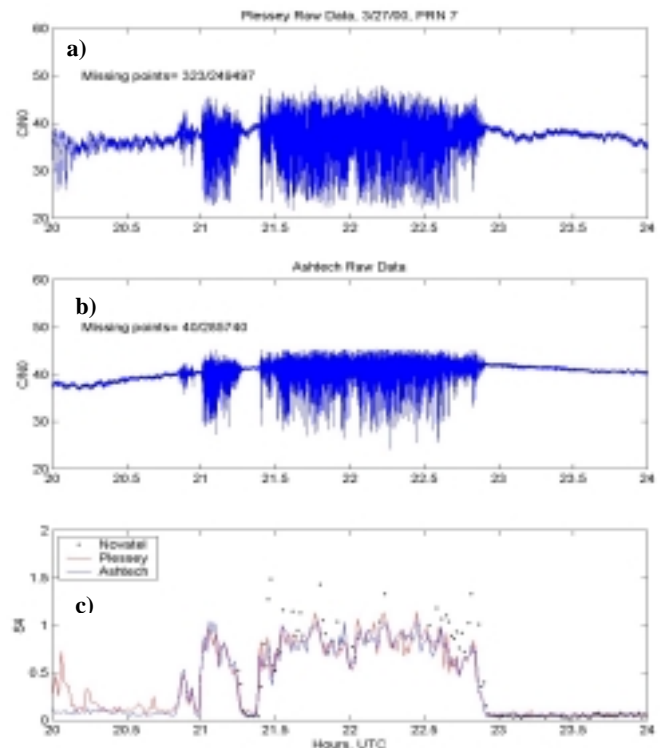


Figure 1. Data collected 27 March 2000 a) 10 Hz C/N₀ from the Plessey Receiver; b) 20 Hz C/N₀ from the Ashtech and c) Comparisons of S_4 calculated over 60 sec intervals from the Plessey, Ashtech and ISM

high data rate C/No measurements from the Plessey (Fig 1a) and the Ashtech Z-12 (Fig 1b), while the lowest panel provides direct comparisons of the S4 values, computed over 60 seconds, from all three receivers. Antennas for the Ashtech and the ISM were co-located on the same rooftop; the Plessey antenna was separated from the others by approximately one kilometer.

While the absolute C/No values reported by the Ashtech and Plessey receivers are somewhat arbitrary, a comparison of the relative fluctuations shows that the two are very consistent. An inspection of the missing data points on Fig 1a and 1b show that the Plessey typically loses more data than the Z-12, though the percentage of lost raw data points is very low and has no effect on calculating statistical scintillation parameters. Interestingly enough, the data losses are highly correlated with strong scintillation periods so they may actually correspond to receiver drop-outs.

In terms of S4, the normalized standard deviation of the signal plotted in Fig 1c, the agreement between the Ashtech and the Plessey is quite impressive; the point-to-point differences are negligible and no bias is evident in the data. The ISM tracks S4 well through weak-moderate scintillation, but generally reports values which are too high in strong scintillation. Moreover, during the strongest scintillation periods the receiver can fail to report scintillation parameters at all, as is evident in Fig 1c by several missing ISM data points between 22-22.5 UT (the ISM did not begin tracking the satellite until approximately 21:30).

The Ashtech Z-12 and the Plessey provide robust C/No tracking through strong scintillation, important for a scintillation monitoring system. However neither receiver has, at present, real-time processing capability. The Z-12's additional capabilities to track phase and obtain total electron content (TEC) data make it particularly attractive for general ionospheric applications.

Navigation

The most significant systems-related issue is whether or not scintillation impacts GPS navigation significantly. The night of 27 March is representative of strong scintillation nights at Ascension Island. Hourly sky maps showing the location of GPS satellites and their relative scintillation level are depicted in Figure 2. The PRN number is plotted next to the start of the track and the size of the circles used to plot the trajectory corresponds to the S4 level. It is clear that from 22-24 UT the majority of satellites are experiencing scintillation at some level (severe levels on 3-5 sats simultaneously). Such nights are not anomalous near the spring and fall equinoxes at locations such as Ascension Island.

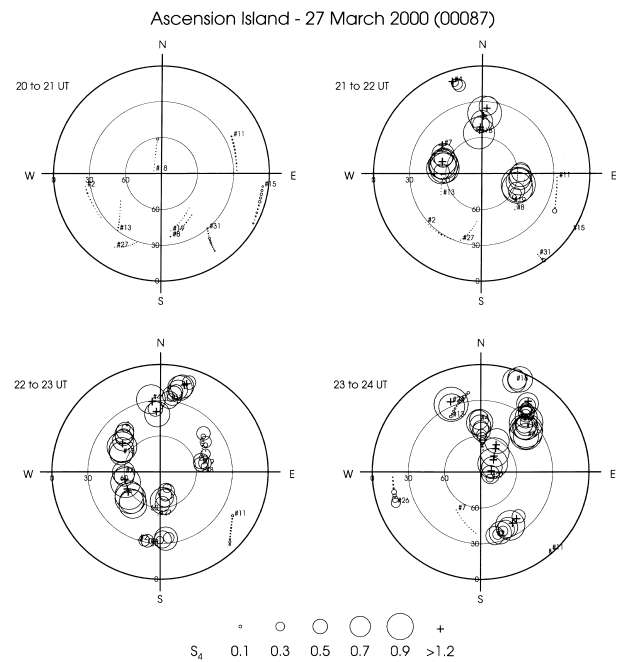


Figure 2. Hourly polar plots of the position and scintillation levels, plotted at 5 min intervals, of all GPS links tracked by the Ionospheric Scintillation Monitor at Ascension Island, 27 March 2000. Circle size corresponds to S4 level as shown in the legend. PRN numbers are plotted at the initial satellite position.

Figures 3, 4 and 5 show positioning data reported by the ISM, the Plessey and the Ashtech, respectively, during the 27 March scintillation event. Consider first the ISM data in Figure 3a-c; it appears the scintillation has little impact on the receiver's position fix. The occasional fluctuations in latitude and longitude are of the order of 100 meters consistent with SA. The ± 100 m altitude variation is also unremarkable. There simply is little, if any, scintillation induced effect on the ISM's navigation.

The data shown in Fig 3d-e may provide an important clue as to why the ISM, which appears to have difficulty tracking through severe scintillation, should be immune from scintillation effects on its positioning. Fig 3d shows the highest S4 values measured by the receiver for any satellite above 30° elevation angle versus time, while Fig 3e depicts the number of satellites tracked by the ISM over the same period. As the scintillation activity increases, the number of satellites tracked by the receiver decreases until, by 22:30 UT, the ISM is tracking only four satellites, the minimum number required to determine a space-time coordinate fix. The ISM appears to drop the "noisy" links and continue to navigate with the clear links available to it.

Position data for the Plessey is shown in Figure 4a-c. The Plessey data shows again the effect of SA which produces

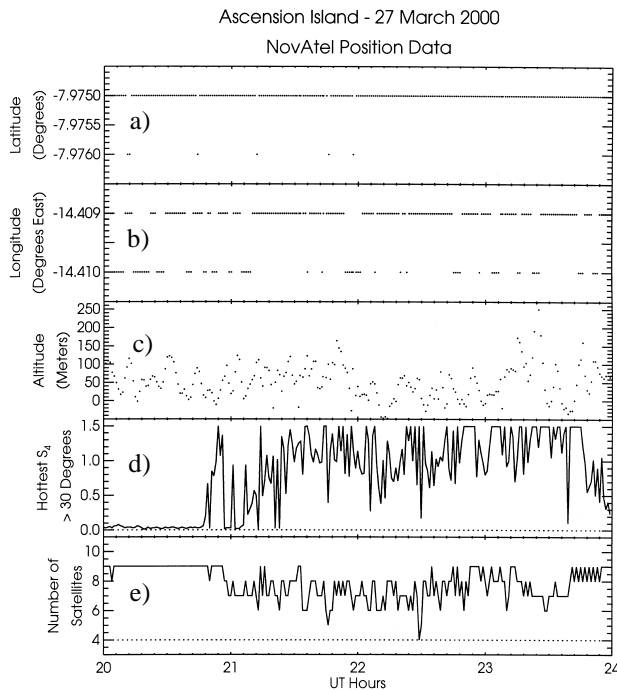


Figure 3. ISM receiver position data a) Latitude; b) Longitude, and c) Altitude. Panel d) depicts the highest S4 observed on satellites at 30° or higher elevation angle, and e) the number of satellites being tracked by the ISM

slowly varying fluctuations in the receiver's reported position. However, between 22.8 and 22.9 UT simultaneous abrupt jumps in latitude, longitude and altitude are observed. During this brief period as many as five satellites were experiencing strong scintillation with S4 at or near unity, and only one or two exhibited no scintillation at all.

Turning at last to the Ashtech, it is immediately obvious that scintillation had a dramatic impact on the receiver's ability to navigate. Inspection of Figure 5a-c reveals intermittent position reporting beginning just before 22 UT with complete outage occurring sometime after 22:30 UT. Shortly before midnight the receiver attempted to recover, reporting positions with errors measured in kilometers rather than meters. Navigation is restored when the scintillation decreases approximately 20 minutes after midnight UT.

The bottom panel in the figure depicts the number of satellites not scintillating during the outage period. In the heart of the event nearly all satellites are experiencing some level of scintillation. However, based on the C/No recorded and plotted in Figure 6a, the Ashtech apparently was tracking at least seven satellites during the entire outage period. Unlike the ISM, which dropped scintillated links and maintained position information, the Ashtech appears to have tracked the disturbed links and attempted,

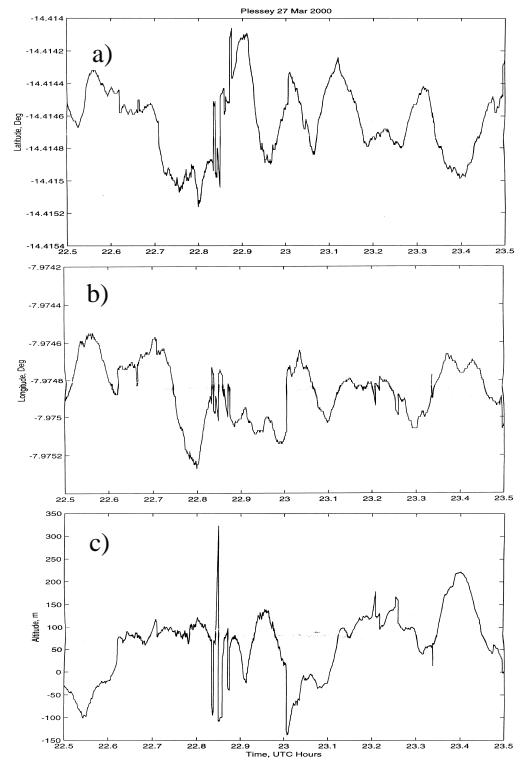


Figure 4. Plessey receiver position data a) Latitude, b) Longitude and c) Altitude.

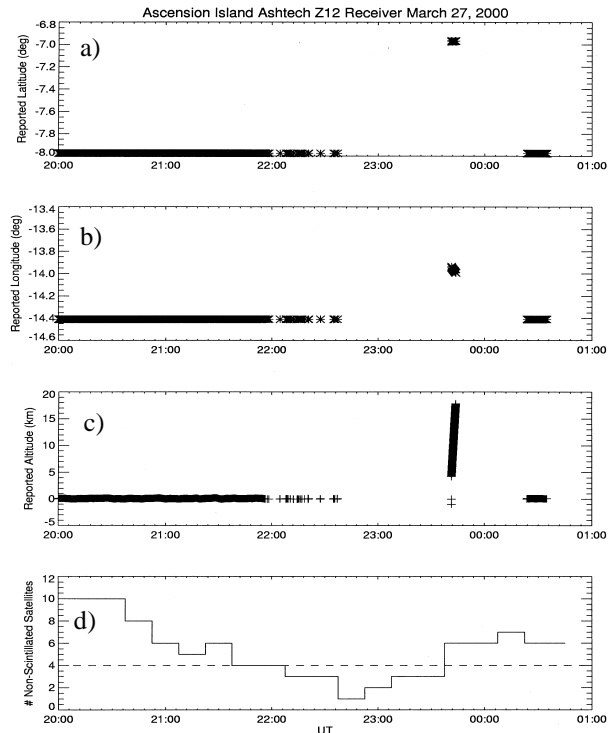


Figure 5. Ashtech Z-12 Position data a) Latitude, b) Longitude and c) Altitude; panel d) shows the number of satellites free of scintillation during the period.

unsuccessfully, to utilize them for navigation. The S4 values corresponding to the C/No data are plotted in Figure 6b.

Initially it was suspected that the apparent outages may have been related to the custom software developed to obtain the 20 Hz C/No samples. However, an identical Ashtech receiver was operated at the same location and sampled at only 0.5 Hz rate and experienced nearly identical navigation errors.

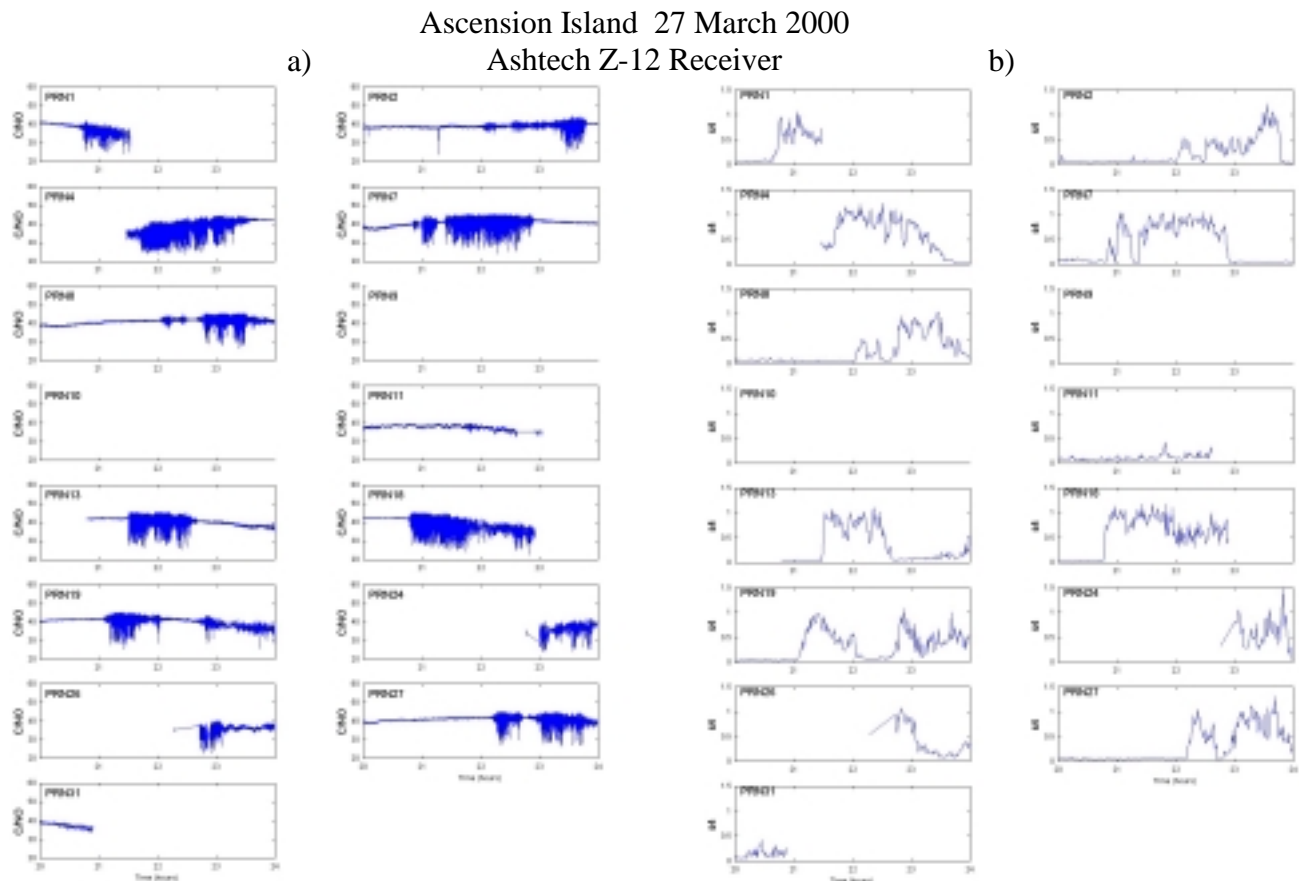
Similar navigation outages were observed on the Ashtech Z-12 on 4 of the 8 nights of observations; data from the other 3 nights are shown in Figures 7 & 8 which depict both the scintillation activity and the associated navigation errors/outages. It is interesting that the outage that occurred on 28 March was not accompanied by the brief periods of very large positioning errors observed on other days when navigation was degraded or absent. It should be noted that only the amplitude scintillations have been presented here, and the associated phase scintillations, potentially having more impact on the receiver, are only now being analyzed. AFRL is currently investigating these data to determine the precise conditions under which the navigation is compromised in an attempt to better understand how the receiver is

affected by the scintillation environment.

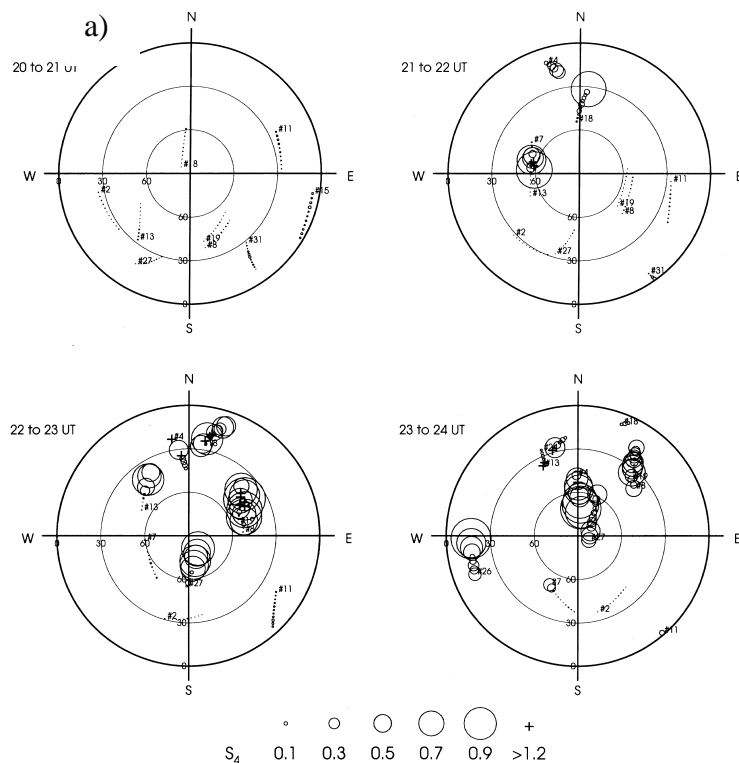
DISCUSSION

The implications of the Ashtech's behavior with respect to modeling the effects of scintillation on navigation performance are of some interest. At a minimum, such modeling requires knowledge of 1) the spatial distribution of scintillation activity and 2) the response of a GPS receiver to a scintillated satellite link. By exploiting GPS for monitoring scintillation, much has been learned about the former in the past few years, while relatively little is known about the latter.

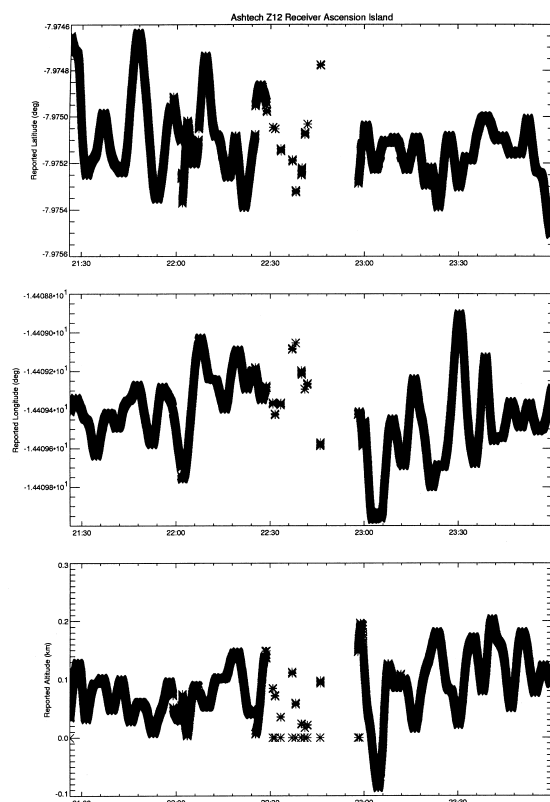
One tractable approach to model scintillation impacts is to assume that each receiver has a "scintillation threshold"; when scintillation on a particular link exceeds that threshold, the receiver drops the link and utilizes other available satellites for navigation. Increased position errors can then be determined simply by calculating the increased dilution of precision (DOP). Such an approach requires "only" specification of the scintillation environment and knowledge of a given receiver's tracking threshold or scintillation link margin. A model based on this premise might provide meaningful results when



Ascension Island - 28 March 2000



b)



Ascension Island - 29 March 2000

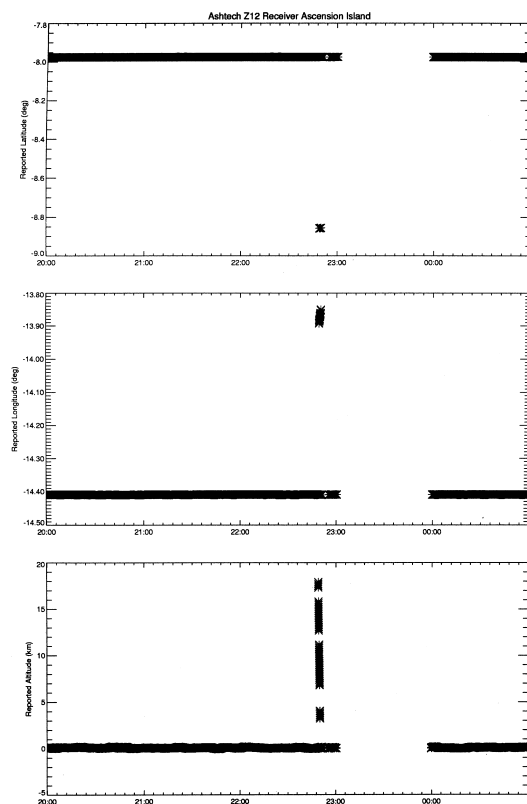
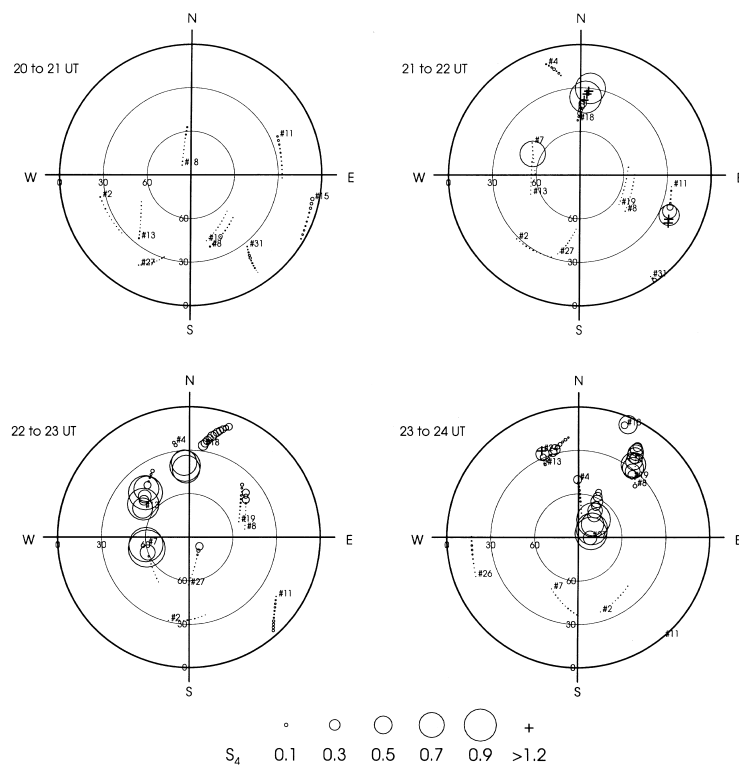


Figure 7 a) Hourly polar plots of the position and scintillation levels, plotted at 5 min intervals, of all GPS links tracked by the ISM at Ascension Island, 28-29 March 2000. Circle size corresponds to S_4 level as shown in the legend. PRN numbers are plotted at the initial satellite position; b) Corresponding position data reported by the Ashtech Z-12

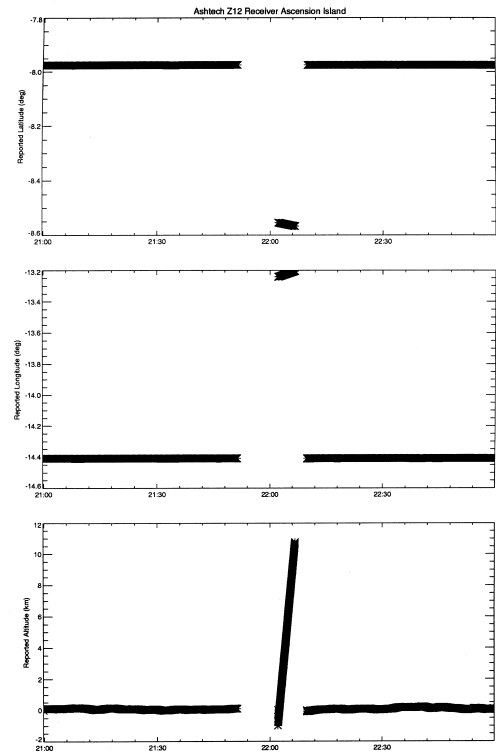
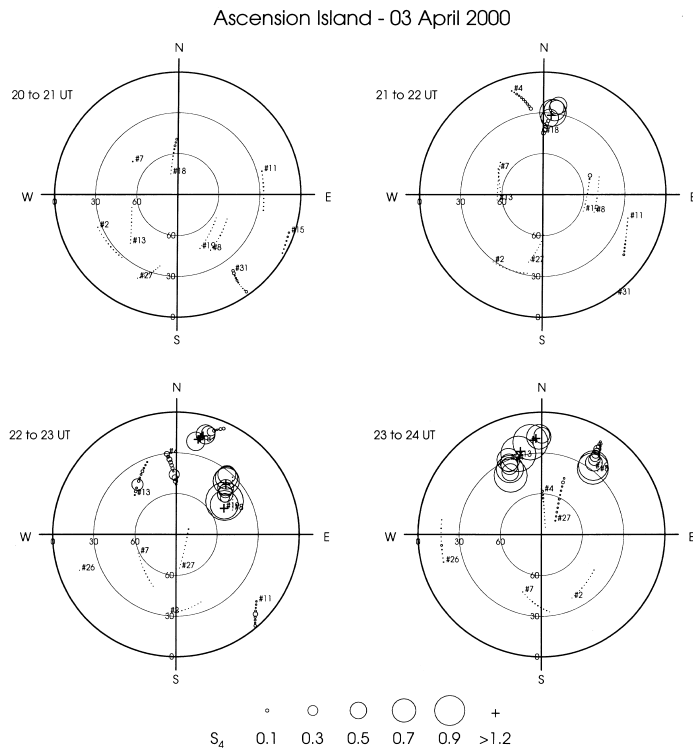


Figure 8 a) Hourly polar plots of the position and scintillation levels, plotted at 5 min intervals, of all GPS links tracked by the ISM at Ascension Island, 4 April 2000. Circle size corresponds to S_4 level as shown in the legend. PRN numbers are plotted at the initial satellite position; b) Corresponding position data reported by the Ashtech Z-12

applied to a receiver like the ISM, for example, but the results presented here indicate that such a model would not be valid in general.

Hardware simulations of the Ashtech's performance in strong scintillation showed it to be extremely robust in tracking disturbed signals on a particular link [Bishop, et al., 1998]. Indeed, the field data presented in the previous section confirm this result. However, the simulations were not capable of completely recreating the real world environment, and the navigation impacts reported here were neither known nor expected based on the outcome of the simple link margin simulations.

The results demonstrate that knowledge of a receiver's ability to track and maintain lock on a perturbed signal is insufficient for understanding how the overall system's navigation will be affected by such signals. The conclusions are that the impacts of scintillation on GPS navigation are both receiver- and application-specific, and must be tested under real-world conditions for accurate assessment.

CONCLUSIONS

The results of testing the performance of three GPS receivers at Ascension Island indicate that the Ashtech Z-12 receiver can provide robust amplitude scintillation monitoring capability as well as phase scintillation and total electron content (TEC) information. On fully half of the nights on which observations were conducted, however, the Ashtech experienced navigation outages ranging from 20-90 minutes duration. Such outages may be more routine than anomalous at low-latitudes during solar maximum.

The observations at Ascension Island and other sites maintained by AFRL indicate that scintillation commonly occurs on more than one link, and may be severe on as many as five or six GPS links simultaneously. In this sense, Ascension Island, located at 16° magnetic latitude, is not a "worst-case" location; it is situated on the southern edge of the peak scintillation region and scintillation events frequently do not extend south of the station latitude. Thus, GPS satellite links to the south are frequently unaffected by scintillation. Scintillation is still

severe and sky-coverage is greater at 12°-14° magnetic latitude, and these regions may be even more susceptible to widespread navigation impacts.

The data collected here underscore the importance of testing GPS applications during the solar maximum period (2000-01). The varied behavior of the receivers suggests that real-world end-to-end tests be conducted for critical GPS applications to insure that any potential degrading effects, such as those caused by scintillation, are identified and accurately assessed. Understanding these effects remains an important goal and presents a formidable challenge for the modeling and simulation community motivated to incorporate scintillation impacts into GPS performance simulation algorithms.

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